Stability Analysis of More Electric Aircraft Power System with 18-Pulse ATRU Feeding Constant Power Loads

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Abstract

With the development of the concept More Electric Aircraft, multi-pulse Auto-transformer Rectification Unit(ATRU) becomes significantly important in aircraft power supply system. However, it brings a stability problem which is a key factor to safe system operation. In this paper, the structure and principle of 18-Pulse ATRU is mainly discussed firstly. Then simulation is undertaken to analyze the impact of 18-Pulse ATRU on system operation characteristics and stability when it supplies power for Constant Power Loads (CPL), which gives theoretical and practical experience for system operation security.

Keywords

MEA; Stability; 18-pulse ATRU; Constant Power Loads

Introduction

Traditional aircraft has such secondary energy as hydraulic, pneumatic, mechanical, which are too heavy and occupy too much space. So in order to gain better performance and higher reliability, secondary energy is substituted by electrical power. This is the concept of More Electric Aircraft. More Electric Aircraft has more power loads which consume large amount of electricity than traditional aircraft. Additional loads categories, especially the application of constant Power Loads, put more requirements on power supply system. Therefore, multi-pulse rectification is used to make the power supply characteristics meet the requirements of aviation power standards [1-3].

There are 6-Pulse, 12-Pulse, 18-Pulse, 24-Pulse and 36-Pulse rectifications in the multi-Pulse category and the transformers include isolating transformer and auto-transformer. The more pulses it has, the better it works, and the less harmonics it generates. But it costs more. For example, by comparing with 6-Pulse and 12-Pulse ATRU s, the 18-Pulse ATRU is able to transmit more power, has smaller size, reduces harmonics and improves power factor, which is similar to 24-Pulse and 36-Pulse ATRUs, but the latter has more complex structure. The operation and stability of power system with 18-Pulse ATRU feeding resistor loads have already been researched, but that of power system with 18-Pulse ATRU feeding CPL needs to be further discussed.

In the power supply system with 18-Pulse ATRU, such parameters as the leakage reactance, the balance reactor, the DC bus resistor and filter, all contribute to the stability of the system. Among them some parameters are of great importance to decide system stability, while the synthesis of all the parameters must also be considered [2,4-10]. Because of its nonlinearity and strong coupling, the stability influence relationship is difficult to be written in explicit expression，so it is better to study the relationship through experimental methods.

Modeling and Analysis on Power System with 18-Pulse ATRU

To build 18-Pulse ATRU model, a concrete realization technique is needed to be given. Although the existing methods provide several choices, however, its essence is to realize phase shifting transformer, which consists of three groups of three phase AC voltage source with 20 degrees angle lagging the previous one. Auto-transformers include tapped auto-transformer and non-tapped auto-transformer. Most of their

characteristics were concluded in paper [1]. One typical and easier achieved auto-transformer is polygon auto-transformer, as shown in Fig.1. Fig. 2 shows 20 degrees phase shifting between Va', Va, Va''.

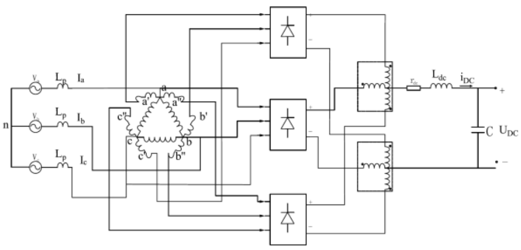

FIG. 1 TOPOLOGY OF 18-PULSE ATRU SYSTEM

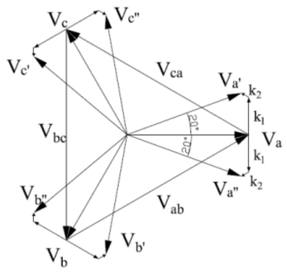

FIG. 2 PHASE-SHIFTING DIAGRAM OF VA', VA, VA''

Each group of three phase AC source forms a 6-Pulse rectification. Because at the same time different groups of AC source have 20 degree phase displacement, inter-phase reactors can be added to make sure it works properly. Fig.3 shows the diagram of inter-phase reactor.

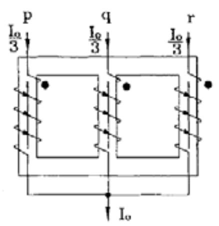

FIG. 3 STRUCTURE OF 18-PULSE ATRU INTERPHASE REACTOR

In this simulink model, the auto-transformer is built by using Multi-Winding Transformer in Fig.4.

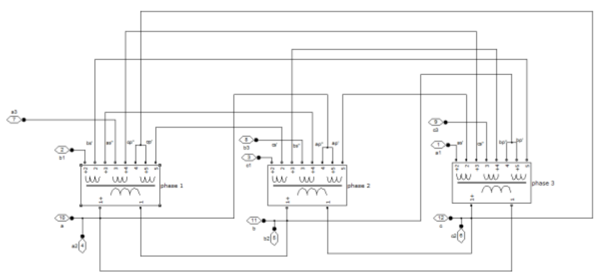

FIG. 4 SIMULINK SIMULATION MODEL OF 18-PULSE AUTO-TRANSFORMER

To validate this model, a resistor is added to the end to obtain the AC current wave in Fig. 5, in which totally there are 18 steps in one cycle, so it is called 18-Pulse rectification system. Analysis of AC current waves indicates that 17-order and 19-order harmonics constitute the main harmonics.

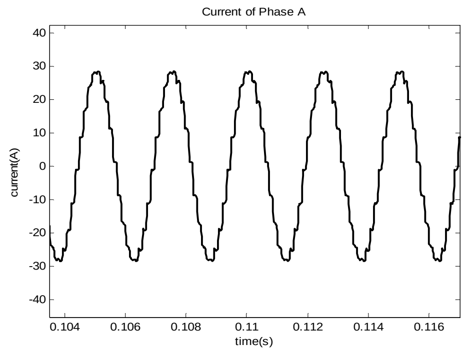

FIG.5 AC CURRENT OF POWER SYSTEM WITH 18-PULSE ATRU

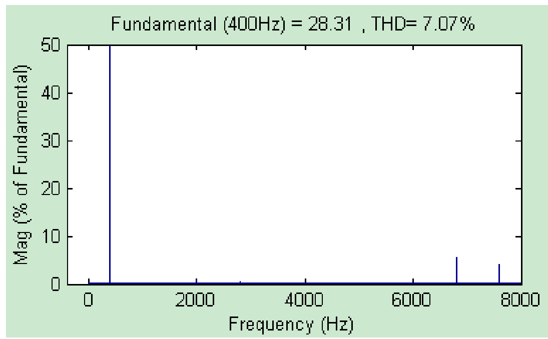

FIG. 6 HARMONICS SPRECTRUM OF AC CURRENT FOR POWER SYSTEM WITH 18-PULSE ATRU

Further, a 5kW CPL was added to the end, which yielded the same result.

Measurement of System Load Capacity with Different Leakage Inductance Equivalent Value

To analyze load capacity of power system with 18-Pulse ATRU and its effect on AC side, an aircraft power supply system in Fig. 7 is built by mainly using this 18-Pulse ATRU. Different leakage inductance equivalent value is measured and CPL capacity is tested.

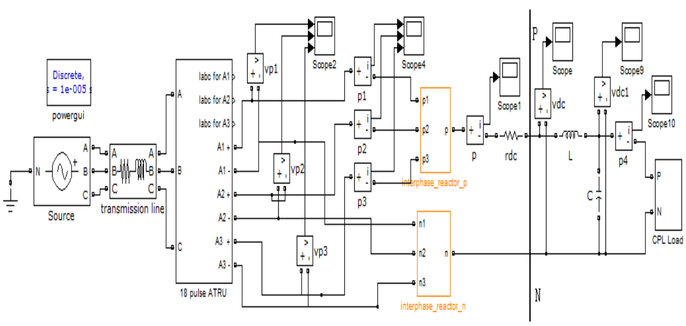

FIG. 7 THE SIMULINK MODEL OF AIRCRAFT POWER SUPPLYING SYSTEM WITH 18-PULSE ATRU

The test program is classified into three groups，each group corresponding to one power factor. Under each power factor，it is subdivided in terms of varied LC proportion，then equivalent DC resistor on the left side of PN and the limit CPL capacity will be tested. The result is shown in Table 1. In Table 1, PF means Power Factor, and the value of rdc equals 0.5 in this simulation.

In accordance to every power factor, serial alphabets are given as A, B, C. For the total cases, a number is added to each letter, such as A1, B1 and C1, etc.

TABLE 1 SIMULATION RESULTS OF AIRCRAFT POWER SUPPLY SYSTEM WITH 18-PULSE ATRU FEEDING CONSTANT POWER LOADS

number	auto-transformer primary winding equivalent leakage inductance L_σ(power factor)	different proportion of L,C [L,C]/[mH, μF]	equivalent DC resistor R_0/Ω	limit CPL load capacity/ kW
A1	0.05mH （PF=0.99）	0.025,1000	0.55	32
A2		0.0125,2000	0.55	32
A3		0.05,500	0.55	29
B1	0.5mH (PF=0.97)	0.025,1000	0.82	7
B2		0.0125,2000	0.82	7
B3		0.05,500	0.82	7
C1	0.65mH (PF=0.95)	0.025,1000	1.1	5
C2		0.0125,2000	1.1	5
C3		0.05,500	1.1	5

From the simulation result it can be shown that, with the increasing of Lσ value, the equivalent DC resistor becomes larger, but the CPL capacity becomes weaker (from 32kW to 5kW). This indicates that the auto-transformer primary winding equivalent leakage inductance has great influence on the CPL capacity.

By using of the model shown in Fig.7, with parameters Lσ=0.05mH, rdc=0.5ohm, Ldc=0.1mH and changing source frequency between 360Hz and 800Hz, the equivalent DC resistor and the relevant limit CPL capacity are calculated, which are listed in Table 2.

TABLE 2 EQUIVALENT DC RESISTOR AND ITS CPL CAPACITY UNDER DIFFERENT FREQUENCY

Frequency/f（Hz）	Equivalent DC resistorR0/Ω	CPL load capacity/kW
360	0.544	32.5
400	0.551	32.3
500	0.573	29.6
600	0.578	26.1
700	0.567	24
800	0.602	21

It can be seen from Table 2 that the CPL capacity decreases with the equivalent DC resistor increases when the frequency rises. This indicates that in a variable frequency power system, the CPL capacity will also fluctuate.

Measuring and Analysis on the Equivalent Internal Resistor of Power System with 18-Pulse ATRU

From above simulation results and analysis, it can be seen that CPL capacity has close relation with the inner equivalent resistor on the left side of PN, so its dynamical variation value with load current and its stable value with different winding leakage inductance are discussed in the following part.

Equivalent internal resistor of power system with 18-Pulse ATRU is measured under different auto-transformer primary winding leakage inductance and resistive load, whose simulation model is shown in Fig. 7.

From the former system structure and principle it can be pointed out, auto-transformer primary leakage inductance will be the essential factor to affect its working characteristics. Parameters are set as L=0.1mH and C=1000μF. Then several Lσ values are collected（individually 0.005、0.05、0.1、1 and 5mH）with a set of resistor loads RL（120,100,80,60,40,30,20,10ohm）. By using of the current Is1 and voltage Us1 that are shown in Fig.7 under different resistor load, R0 is obtained by formula R0=ΔU/ΔI.

The results for five cases are listed in Table 3.

Based on the data in Table 3, five curves can be drawn in Fig. 8.

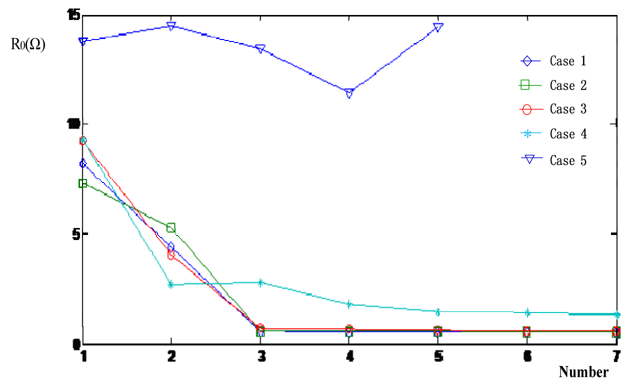

FIG. 8 CURVES OF FIVE R0 CASES

It can be seen from Fig. 8 that:

Under same leakage inductance, R0 decreases obviously first and then keep almost same value (with resistor load between 10 and 40ohm) with the decrease of the load resistor.

When the load resistor pairs for each leakage inductance doesn't change, R0 increases along with the rising leakage inductance.

Due to the statistics in Table 3，the output DC voltage and DC current relationship can be plot in Fig. 9.

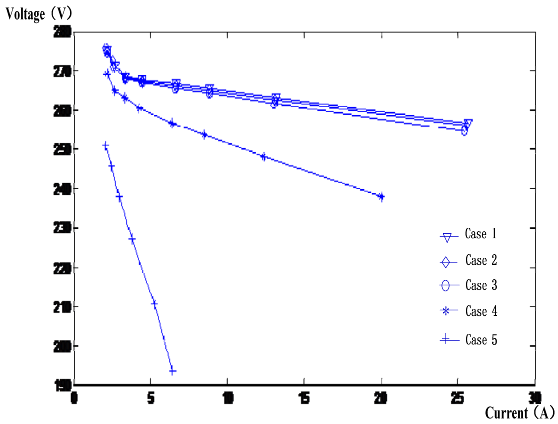

FIG 9 THE RELATIONSHIP BETWEEN DC VOLTAGE AND CURRENT

It can be shown from Fig. 9 that, the relationship between output voltage and current is nonlinear in each leakage inductance case, while it becomes linear when the output current is larger than 6A（Lσ<1mH）. Therefore the 18-Pulse ATRU plays a important role in system operation. And the voltage current curve becomes steeper as the leakage inductance becomes larger. It should be emphasized that the voltage reduces in accordance with the leakage inductance decreasing at the same current level. So auto-transformer primary winding's leakage inductance has great effect on system operation.

The Measuring of CPL Limit Capacity with Different Leakage Inductance

The above analysis shows that power system with 18-Pulse ATRU has nonlinearity characteristics, so the CPL capacity for this system is also should be studied.

Under every leakage inductance condition, by using the same filter parameter, its relative limit CPL capacity is obtained. The result is listed in Table 4.

R0 value is selected when power system with 30ohm resistor load. Simulation has been carried out to test the limit CPL load capacity. Table 4 indicates that the limit CPL capacity decreases very quickly as the leakage inductance increases.

Stability Analysis of Power System with 18-pulse ATRU Feeding CPL

In paper [2], the criterion of judging the stability of a HVDC (High Voltage DC) circuit is introduced, but it is not as to a power system with 18-Pulse ATRU from the analysis results above. In the following section, the relative issues on system stability will be discussed.

TABLE 3 TESTING RESULT OF R0 WITH FIVE DIFFERENT Lσ VALUES

No.		**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**
	Lσ（mH） **RL(ohm)**	**0.005**	**0.05**	**0.1**	**1**	**5**
1	120	8.2	7.333333	9.25	9.318182	13.78378
2	100	4.384615	5.3125	4.026846	2.727273	14.47619
3	80	0.588235	0.590909	0.725953	2.8	13.41615
4	60	0.501139	0.590909	0.688705	1.809524	11.42857
5	40	0.536364	0.552995	0.597701	1.464844	14.43478
6	30	0.513953	0.534884	0.588235	1.424212	
7	20	0.5128	0.522928	0.582996	1.312336	

TABLE 4 CPL CAPACITY WITH DIFFERENT LEAKAGE INDUCTANCE

No.	**Primary Winding Leakage Inductance Lσ(mH)**	**L , C Ratio[L,C]/[mH,μF]**	**DC equivalent resistor R0/Ω(Load Resistor equals 30ohm)**	**Limit CPL load capacity P1/kW**
1	0.005	0.1，1000	0.514	35.1
2	0.05	0.1，1000	0.535	32.75
3	0.1	0.1，1000	0.588	24.2
4	1	0.1，1000	1.42	4.5
5	5	0.1，1000	13.42	1.28

TABLE 5 CONSTRAST BETWEEN LIMIT CPL CAPACITY BY SIMULATION AND THAT CACULATED BY THE CRITERION

No.	Lσ(mH)	L，C ratio[L,C]/[mH,μF]	DC equivalent resistor R0/Ω(resistor load=30ohm)	Limit CPL load capacityP1/kW	Limit CPL load capacity caculated by the criterion P0/kW ($P_0 = \frac{V_s^2}{4R_0}$)	VS	$k_1 = \frac{V_s^2}{4R_0P_1}$
1	0.005	0.1，1000	0.514	35.1	35.422	269.87	1.009
2	0.05	0.1，1000	0.535	32.75	33.944	269.52	1.036
3	0.1	0.1，1000	0.588	24.2	30.85	269.37	1.275
4	1	0.1，1000	1.42	4.5	12.385	265.6	2.752
5	5	0.1，1000	13.42	1.28	1.44		

TABLE 6 THE CONTRAST OF FILTER INDUCTANCE LCR

No.	Lσ(mH)	HVDC equivalent resistorR0/Ω	VS	Lcr /mH ($L_{cr} = CR_0^2$)	HVDC'L/mH		18-Pulse ATRU'L/mH	
					30kW	20kW	30kW	20kW
1	0.005	0.514	269.87	0.264	0.59	1.26	0.32	0.93
2	0.05	0.535	269.52	0.286	0.58	1.27	0.3	0.85
3	0.1	0.588	269.37	0.346		1.28		0.87

The equivalent simple HVDC circuit is shown in Fig. 10, in which Vs is the equivalent DC voltage source, R is a synthesized resistive parameter, L is a synthesized inductive parameter , C is filter capacitor, and P0 is the power of CPL.

As to circuit shown in Fig.10, by using Mixed Potential function theory in paper，the stability criterion can be written as：

$$\sqrt{\frac{L}{C}} < R < \frac{V_s^2}{4P_0} \quad (1)$$

This criterion means：

(1) inequation $R < V_s^2/(4P_0)$ in (1) can be used to judge whether there is an equilibrium point for system. If the CPL capacity cannot satisfy this criterion，the system won't operate at an equilibrium point, that is, the CPL cannot be driven by this power supplying system;

(2) inequation $R > \sqrt{L/C}$ in (1) is to estimate the stability status. If the parameters of LC filter match this criterion，the damping of system is positive (stable), or else it is negative (unstable).

Employing the tested R0 value under 30ohm resistor load , the calculated source voltage and the adopted LC value, the theoretical CPL limit capacity can be determined by using of inequation $R < V_s^2/(4P_0)$, which is given in Table 5.

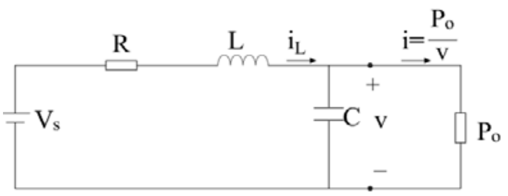

FIG. 10 HVDC EQUIVALENT CIRCUIT

It can be seen from Table 5 that when the leakage inductance is small（e.g. Lσ≤0.05mH），P1 and P0 are very close. However, when it becomes larger（e.g. Lσ≥0.05mH），P1 and P0 differ from each other greatly.

Meanwhile，it can also be known that P0 is higher than P1, and as the leakage inductance becomes bigger, their difference is larger. So taking advantage of equation $k_1 = \frac{V_s^2}{4R_0P_1}$, a correction coefficient k1 need to be added to stability criterion of power system with 18-Pulse ATRU feeding CPL. k1 varies nonlinearly in correspondence to leakage inductance by comparing the theoretical value and simulation value P1.

In the next section, we utilize the already obtained R0 by each leakage inductance and employ the criterion given in paper to calculate the demanded filter

inductance. As a contrast, the filter inductances L in a HVDC model determined by using criterion of the limit inductance ($L_{cr} = CR_0^2$)and that in power system with 18-Pulse ATRU obtained by simulation are listed in Table 6.

For the sake of simplicity, this paper uses HVDC circuit to get different limit filter inductance (shown in Fig. 10). Simulation was undertaken under different leakage inductance with CPL power set at 20kW and 30kW separately. The same process is also performed on a power supplying system with 18-Pulse ATRU. It shows that limit filter inductance obtained by the former method is larger than that gotten by the latter method. The reason is that only the filter inductance exists in the simple HVDC circuit while the leakage inductance and interphase reactor are also affecting the total equivalent inductance in circuit with 18-Pulse ATRU. In addition, all obtained L value of the two circuits is bigger than Lcr, so it is safe to set the L value below Lcr when system designing. Therefore, there is no need to modify the judging criterion of inequation $R > \sqrt{L/C}$.

In summary, it is someway feasible to calculate the parameters of 18-Pulse ATRU by using the existing criterion by making some adjustments for simplicity. Then inequation (1) criterion should be modified as the following form:

$$\sqrt{\frac{L}{C}} < R < \frac{V_s^2}{k_1 4P_0} \qquad (2)$$

Inequation (2) has the same function as inequation (1).

Conclusion

In order to analyze operation characteristics and stability of power system with 18-Pulse ATRU feeding CPL. The 18-Pulse ATRU simulation model is built in this paper firstly. Then the influence of system parameters on system working effect, CPL capacity and stability issue are discussed. Finally, some interesting results were derived.

For a power system with 18-Pulse ATRU, Leakage inductance has great impact on system operation characteristics, especially on the equivalent source internal resistor and CPL capacity.

The source frequency also has influence on equivalent source internal resistor and the CPL capacity.

For a power system with 18-Pulse ATRU, it is simple to use similar criterion of equation (1) to make a judgment, but it should be corrected by introducing coefficient to the right side of the criterion while the left side of the criterion keep unchanged, which is given in equation (2).

The above conclusion for MEA power system with 18-Pulse ATRU has guiding significance for application.

ACKNOWLEDGMENT

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